Journal of Innovative Technology, Vol. 7, No. 2, pp. 9-21, September 2025
http://doi.org/10.29424/JIT.202509_7(2).0002

Recent advances in fault detection, classification and isolation techniques for smart grids: a review

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ABSTRACT

Every electric power system necessarily consists of one or more power sources, transmission lines and loads. Conventional and renewable power sources are part of the electric system. The word “smart grid” got attention in in the early 2000s and research in said domain started with development in renewable energy sources and digital communication technologies. Interest in this field grew swiftly with the increased focus on efficient energy sources, grid reliability, and distributed energy resources integration. Initial stage pilot projects and foundational studies with large-scale implementations emerged around 2010, coinciding with policy support and funding initiatives worldwide. The world is giving attention to transitioning to renewable sources of energy to slow down the adverse effect of climate change and minimize the use of polluting material and fossil fuels. Artificial intelligence and machine learning-powered smart grid effectively integrates renewable resources, manages the demand-supply and empowers the consumers to dynamically participate in the energy ecosystem to promote a culture of energy conservation and improved sustainability. The aim of the study is to have a thorough survey of existing artificial intelligence and machine learning methods and their implementation in smart grids that enhance the efficiency and sustainability of the system and promote green energy deployment.

Keywords: Smart grid, Smart Fault Detection, Identification, Isolation; electric power system, Artificial intelligence; Machine Learning.

1. INTRODUCTION: SMART GRID PRELIMINARIES

A new era electric system empowered with advance technologies such as smart meters and signal sensors is stated as “Smart Grid” intended to enhance efficient and reliable electrical power delivery. The following are some standard definitions of a smart grid as in existing literature.

Definition 1. The Smart grid is an advanced digital bidirectional power flow structure capable of adaptive, resilient, self-healing and sustainable with prudence for prediction of various uncertain conditions [1].

Definition 2. The Smart Grid may be an electric system that utilizes computational intelligence and bidirectional communication in a unified manner over the whole spectrum of the electric system from the generating stations to load ends [2].

Definition 3.A Smart Grid (SG) has the ability of Controlling passive and active networks wisely to enable the integration of different renewable energy sources into the electric network [3].

Definition 4. The unified, transparent, and instantaneous two-way delivery of electric power and its relevant data, allowing the electric industry for better arrangement of energy transmission and delivery and authorizing consumers to have extended control over energy utilization. [4]

1.1 Smart grid overview

An SG is a sort of self-managing network, seen as the future of control and protection systems. It is a fully or partially automatic system of monitoring, control and protection devices that increases the dependability of the electricity transmission by avoiding frequent supply break-ups. It exploits information technology to improve electric grid capability and reliability. It may be built on existing grid components such as sensors, meters, relays and other energy management systems i.e., PLC, SCADA, etc., by adding new algorithms and utilizing data more effectively. Smart grid (SG) is viewed as the new generation of electric power grids, due to improved efficiency, maximized utilization, reduced cost, described demand and precise gaseous emission [20]. Smart Grid (SG) has high penetration of renewable energy resources with high uncertainty, however forecasting effectively as suggested by [5] may overcome this challenge. The term Smart Grid (SG) can be defined as the integration of the existing power grids with a more secure, sophisticated communication and flexible setup. Interoperability feature, is a two-way communication acts as a backbone, is necessary to deal with the communication requirements of each Smart Grid (SG) element, assumed that these fulfill communication requirements with variable degrees of reliability, QoS and security. Smart Grids are fortified with smart sensors that permit them to collect real-time relevant info of the status of all elements of the complete network. Smart grids gained high importance due to its applications in the modern world and attention of many researchers as depicted by the following pie chart. This figure highlights the prominent contributions of researchers in the field of smart grids. Zhang Y appears as the most prolific contributor with 139 papers very closely followed by Wang Y with 120 and Javaid

Manuscript received January 1, 2025; revised March 8, 2025; accepted March 11, 2025.

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N with 115, representing their significant impact and interest in the said field. Liu Y, Siano P and Li Y, with 97, 101 and 86 papers respectively, are also some of the main contributors. This data underlines the depth of diverse and expertise contributions from individuals globally, highlighting a robust and continuously evolving field of research.

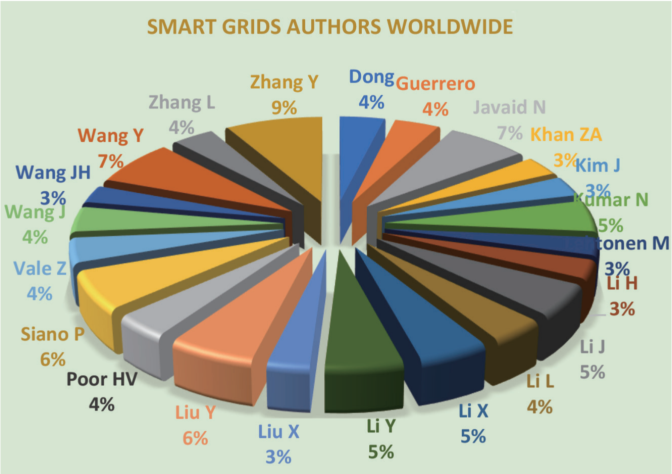


Fig. 1 Contribution of researchers in the field of smart grids worldwide

Open high voltage transmission of electric power is unavoidable, but the main concern of electric power system is to preserve the consistency of the grid. Increased power demands introduce concerns about overloading, increased risks of voltage sags and system's potential level stability. Strengthening the control and protection methods is necessary to prevent a locally occurring fault from spreading to other segments of the grid. The motivation and framework for development of a multifaceted control and protection method that starts with local measurement instruments and combined with higher-level control strategies into an overall control methodology.

The word grid refers to the massive web of transmission lines, secondary and tertiary substations, distribution lines, transformers, and other related assets and machineries that deliver or help in delivering electricity from the power plants to loads like ore houses or businesses. A grid is a mesh of one or more kind of power sources, loads, electrical power carrying conductors and many other minor types of control and protective equipment for example relays, circuit breakers, and transformers etc. in the same context, a Smart Grid is an advanced kind of grids that is equipped with state-of-the-art technologies to monitor the minute fluctuation in system's parameters and respond appropriately with slightest delay in time. The application of machine learning and AI strategies with already available protective and controlling mechanism converts a traditional grid into a smart grid. It has the ability to optimize power delivery and generation, accommodate abrupt load variations, predict and self-rectification of faults, deliver noiseless power and encourage consumer participation. The research on Smart Grids, as stated above, started in the early 2000s. The figure given below depicts the No. of research articles per year regarding Smart Grid fault detection techniques. The data shows the continuously increasing international researchers' interest and endeavors in addressing such challenges.

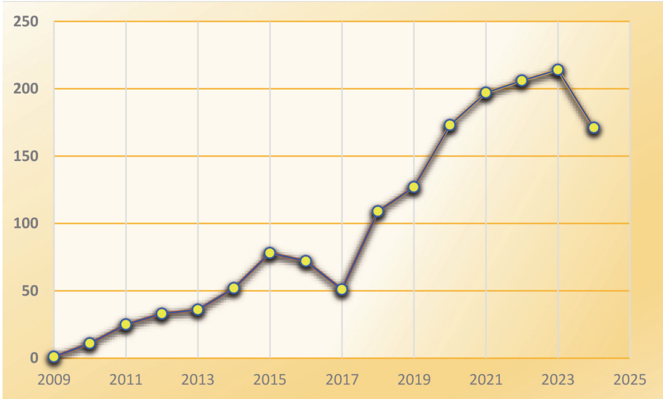


Fig. 2 No. of publications on fault identification per year worldwide

The figure 2 above provides the outline of the number of publications related to Smart Grids as a field of study worldwide reflecting a significant rising trend over the years starting from the very beginning year in which the research started i.e., 2009 up till now. Looking into the given graph, we see that the research started with a single article published in 2009 and after that research went on with a drastic speed in 2018 till now. Statistics show 109 papers in 2018, 127 in 2019, 173 in 2020, 197 in 2021, 206 in 2022, 214 in 2023 and 171 in the year of 2024.

A smart grid (SG) is need of the time because it has a well operator assistance, autonomous control, Efficient and enhanced combination of renewable energy resources (RES). A Smart Grid avails advantages of innovative services and products such as intelligent monitoring, communication, self-healing and controllability properties in relation to (i) facilitate operation and connection of power sources of any size and type; (ii) allow consumers of the service actively participate in optimizing the system operation; (iii) considerably decrease the environmental impact over the whole electric supply system: (iv) improve or preserve the level of system's security, reliability and service quality [21].

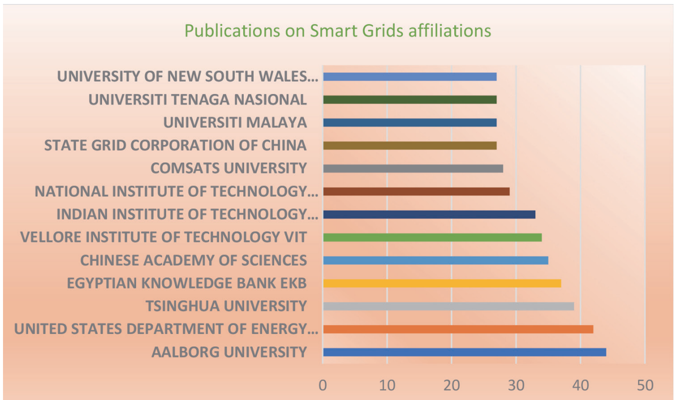


Fig. 3 Publications on Smart Grids affiliations

Fig. 3 above presenting the statistics of research in the field of smart grids with respect to affiliations and the main contributing institutes over the world. Alaborg university leads the community with 44, USDOE with 42, Tsinghua with 39 and CAS with 35 publications highlighting the major players. The chart data filtered out the institutes who have less than 25 publications up till 2024. The smart grid enables utilities to act as partners with consumers to accomplish the demand side of the energy to help minimize the need for costly new infrastructure and to enable consumers to have an oversight and better control of their energy consumption. Similar insights are given in [65] emphasizing the importance of smart grid over traditional grids.

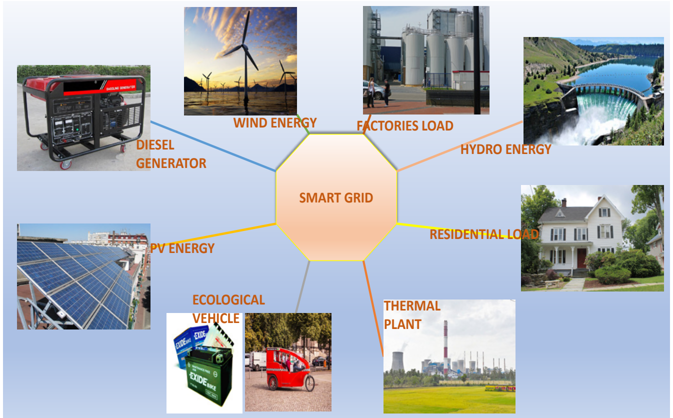


Fig .4 Smart Grid pictorial representation

A Smart Grid (SG) in terms of structure is group of interconnected loads as well as the energy sources with conducting transmission lines working in a coordinated and controlled manner in both islanded and grid connected mode.

1.2 Smart Grid Characteristics

A smart grid is capable of having the following characteristics.

- Resilient – Resistant natural disasters to and attack and extreme weather conditions as it becomes more distributed and strengthened with Smart Grid's security protocols.
- Intelligent – Ability to sense the system's excessive and minor overload and redirecting power to avoid or minimize outages; capable of functioning autonomously whenever conditions need resolution with quicker response.
- Efficient – capable to meet increased and rapidly changing consumer demands without adding further equipment or infrastructure.
- Accommodating – Have the capability of accepting energy from almost any source, i.e., solar, wind and bio-chemical as simply and as natural gas and coal, have the capability of integrating any technological idea, energy storage.
- Opportunistic – making new openings and marketplaces by means of its capability to exploit the plug-and-play property whenever and wherever appropriate.
- Quality-focused – able to deliver the power, load spikes, free of sags, disturbances and with minimum interruptions– to empower fast digital economy, computers, data centers, and all other electronics mandatory to make it run.
- Environment-Friendly – reduces the rise of global climate change and presents an unaffected way toward environmental upgradation by significant decarbonization.
- Costumer friendly – Enabling real-time two-way communication costumer and power company so that the costumers can modify their consumption according to their preferences, such as billing and/or environmental concerns cooperatively in line with the goals of consumers, companies and regulators.

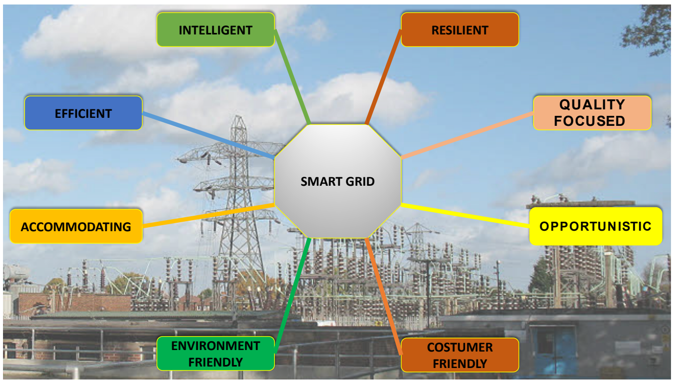


Fig. 5 Properties of Smart grids

2. FAULTS IN SMART GRIDS

A Fault in an electrical system is most of the time, a deviation of voltage, current, and frequency from a threshold value. It may also be in the format of rate change of frequency (RoCoF), intrusion of unwanted harmonics etc. The type of fault may vary according to the type of component of the given Smart Grid (SG). Some common faults are line to line, single/two/three line(s) to ground, open circuit, bridging fault in a PV etc. The main causes of faults are voltage drops, which may cause to either asymmetric line to line (LL) single line to earth (LG), double line to ground (LLG) OR symmetric; three lines to earth (LLL or LLLG) faults. There may be many other types of faults within a smart grid but all of them flare up from one of the earlier stated causes. Due to the increase in demand for load, cost of electrical energy and problematic climate change in the present era, it is need of the hour to shift to renewable power sources gradually and to adapt green energy specifically PV system, batteries and wind power plants. A different aspect in this context is electricity theft which also adversely affects a smart grid is addressed by [22]. Daily operation of Smart grids needs a day ahead load prediction as discussed in [23]. The output power, voltage and other parameters of these resources are difficult to predict because of their irregular nature e.g., the output of PV cells, affected by elements like temperature, weather, and intensity of light. The fusion of these sources, no doubt poses a serious condition to system stability by increased likelihood of occurrence of different faults. The following pie chart is a representation of No. of research papers published by different publishers in the field of fault detection in smart grids with more than 20 the figure highlights the dominance of IEEE, leading with 44% of worldwide data in this field and followed by Elseveir with 23 and Mdpi 17% share. Other prominent publishers are Springer Nature, IET and Wiley.

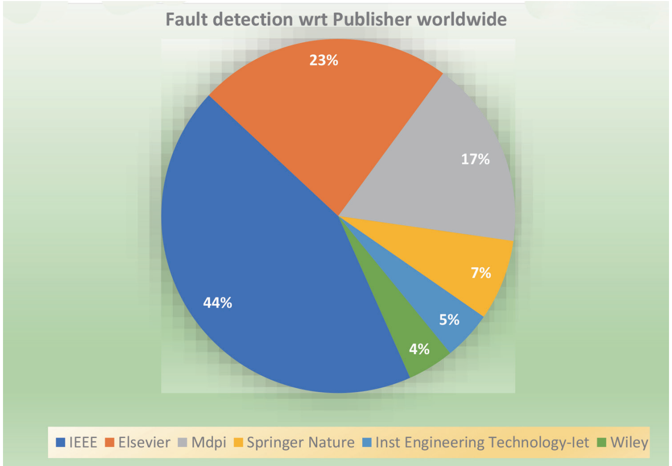


Fig. 6 No. of Research articles on fault detection in smart grids by various publishers.

The incorporation of renewable energy resources (RES) has become safe with the help of smart grids. Faults in these integrated systems may be categorized as soft and hard faults [20]. A hard fault generates sudden changes in the system's parameters, which consequences in an unrestrained change from the normal manner of operation into a defective state. A soft fault results in a nonstop change with respect to the time of a typical system structure parameter, which also results in unknown additive disturbances to set(s) of system's dynamics.

2.1 Fault detection logics

All kinds of fault detection techniques are based on one of the following fault detection logics.

1.Residual analysis
2.Signal processing technique
3.Pattern Recognition
4.Model based approach

1. Residual Analysis

Residues are the value of differences between the observed values and the predicted values. Schematic designs of residual can be used to detect deviation from assumptions. It is a statistical procedure used to assess the fitness of a given statistical model. It involves examining the variances between target data points and the values predicted by the assumed model. These differences, known as residuals. By examining the residuals of a system, we may assess the appropriateness of a model.

2. Signal processing technique

Signal processing is the field of handling and interpreting signals, which are representations of some physical phenomena in the form of pulses, waves or patterns. Signals can be of different forms, e.g., digital or analog, continuous or discrete, random or periodical. It carries information about various aspects of a system's parameter, such as voltage, current, frequency, phase angle, noise and power etc. The received signal is compared precisely with actual original signal to detect faults. Such techniques are adopted due to their stability, effectiveness, versatility and effortlessness of modification.

3. Pattern recognition

A pattern is continuously occurring visual trend of some process. Pattern recognition is a way to analyze the previous trend of an ongoing process and compare it with new trends for finding any kind of anomaly.

4. Model based approach

Mathematical models of many processes of various fields like engineering, physical and chemical are helpful in fault detection. By using an appropriate mathematical model for a system under study can briefly describe a deviation from normal behavior. Some of these approaches include observer-based, parity-space approach and parameter estimation-based methods.

2.2 Importance of fault detection

Contemporary energy systems observing growing penetration of (RES) and sensitive complexity in generation, distribution and transmission components. Occurrence of faults is inevitable in electrical networks. But detecting these faults in electrical systems is of great importance, for both electricity companies and the consumer viewpoint Power system suffers from unforeseen failures due to many causes. Fault localization and prediction can be really challenging whenever dynamical fault currents from RES penetrates the system. Unpredicted faults occurring in power systems are required to avoid propagating to other sections of the power system. The functions of the protective systems are to detect, classify and in the same way determination of location of a fault and to measure the voltage and current magnitudes of the persisting fault. Then in the end, for isolation of the defective section, the protective relays send signal to circuit breaker [15].

Electric faults may result in harm to humans and other living things, system failure, damaging the equipment and electric fires. It is significant to sense the fault in least possible time and to rectify it or even separate the faulty part from the rest of network to avoid major faults like complete shutdown in order to decrease the down time, avoid harm to human beings and other living things and the eruption of electric fires. An effective fault detection and solation scheme is necessary for the safety of components and the stability of the system as a whole. The research in this field is not limited to developed countries as shown in the following table. We observe that different countries are putting their research efforts in the said field from leading countries like China with 439 publications. The USA following China with 293 publications, showcasing its advanced capabilities on energy innovation. India third ranked in this regard and so on.

Table 1 No. of Publications on Smart Grid fault detection region wise

S.No	Region	Publications
1	Peoples R China	439
2	USA	293
3	India	183
4	Canada	103
5	Iran	95
6	Spain	77
7	Italy	69
8	South Korea	59
9	Egypt	57
10	Australia	55
11	England	54
12	Pakistan	48
13	Brazil	48
14	Denmark	30
15	Taiwan	16

3. INTELLIGENT FAULT DETECTION, IDENTIFICATION AND ISOLATION (IFDII)

Intelligent fault detection is the quality of a Smart Grid (SG) to automatically sense a faulty state of a sample circuit's parameters or variables within minimal time span. In addition to detecting faults, an intelligent system also has the capacity of identification of nature of fault. The recent technological developments in the area of Smart Grids (SG) not only detect the fault effectively but can predict the fault earlier than its occurrence, identify the location and even separate faulty section from the system within minimum time. The accessibility of the relevant data makes the system capable of predicting many other features of a given smart grid too, e.g., Load and output forecasting, stability of the system. Table 2 below depicts a comparative analysis of traditional and smart grid in terms of important parameters, underscoring the differences in customers' interaction with system, load management and system's monitoring etc. It demonstrates the importance of advancement in reliability and efficiency.

Table 2 Comparative analysis of Traditional and Smart grids.

S. No.	Feature	Traditional Grid	Smart grid
1	Control technology	Electro-mechanical	Digital
2	Information flow	Uni-directional	Bi-directional
3	Distribution	✗	✓
4	Supervision	Manual	Self/Computerized
5	Generation	Centralized	Distributed
6	Restoration	Manual	Self-healing
7	Advanced algorithms	✗	✓
8	Costumer communication	low	high

Although artificial intelligence has been conceived in the late 1950s, it was obsolete due to unavailability of data as it requires a large amount of training data but presently data scarcity is no more. Intelligent Fault Diagnosis (IFD) discusses the implementation of machine learning techniques to diagnose faults. It has attracted much attention in the previous couple of decades [63]. Intelligent fault detection and identification often refers to the implementation of ML approaches such as ANN, Deep Neural Networks (DNN), K mean clustering, Anomaly detection SVM etc., systematically to the given electrical circuit or the grid. A brief discussion about some of IFD techniques is given below. Figure 7 shows the fault detection concepts applicability in diverse domains. E.g., Engineering, Energy and fuels and Computer science etc. One can observe that the stream of engineering, energy and communication systems are some of the main stakeholder in utilizing fault detection ideas.

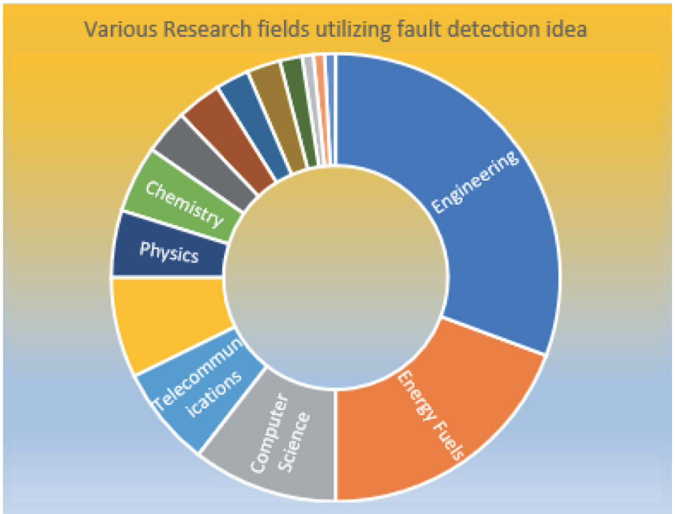


Fig. 7 Various Research fields utilizing fault detection idea

A model-based approach presented in [7] is a scheme for fault sensing and isolation electrical systems such as Smart Grids (SG) based on methods developed in environment of oscillating of systems. In [8], author discusses issues accompanying with enhancing accuracy of fault location approaches in Smart Grids (SG) using large amount of data from intelligent electronic devices. An algorithm that performs fault detection and identification in a decentralized way stated by [9] is a multiscale network inference for fault localization and identification.

The scheme proposed as given by [10] is checked for various shunt faults (either symmetrical or unsymmetrical) and high impedance system faults in the grid having radial and ring structure. It is a form of differential energy- based fault defense metho in microgrid and may be applied to Smart Grid (SG).

Transmission lines are also a necessary part of electric grids. Focusing on faults on electric transmission lines, SVM-based techniques are discussed in [11]. These are special kinds of machine learning programs which are reasonable for fault diagnoses and allow data to shift in one or many classes (single and multi-class SVM), dependent on the application. It is a combination of attribute QSSVM and temporal attribute QSSVM for fault prediction and classification. A method detection of high impedance fault (HIF) occurrence particularly in the overhead distribution networks is stated in [12] is based on signal processing. It is successfully applied in Greek rural Medium Voltage (MV) distribution network, actually situated in the city of Thessaloniki. This method uses Power Line Communication (PLC) technology for HIF recognition and localization. The same may be applicable in Smart Grid (SG).

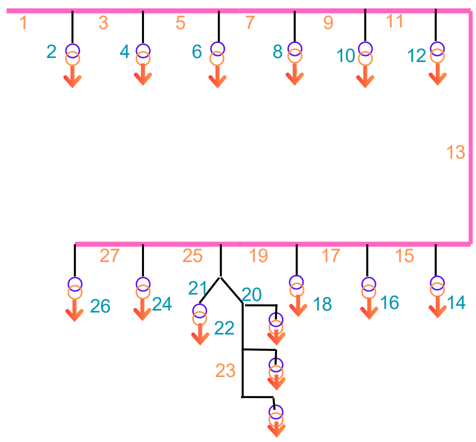


Fig. 8 The network under study [11]

Goertzel algorithm is used for total harmonic distortion (THD) calculation in [13] is a combination of hardware and software. This technique is based on smart meters and microcontroller powered by MATLAB and MATHCAD. This method comes up with a cheap single phase digital power quality measuring equipment for costumers' usage having an extensive range of properties including load trip on failure, series arc-fault detection and neutral/phase line short indication. Although this setup is for an official building, it may be easily applicable to smart grid because of its wireless, low-cost, classification capabilities, an extensive range of monitoring network's parameters, integration flexibility and their derivatives properties. The application of neural network in this field is given in [14], presenting neural network architecture for fault detection in electric power systems specifically in Transmission Lines. Differential method for reliable protection of microgrid by means of time-frequency transform e.g., S-transform [15] is tried for different shunt faults (whether symmetrical or not) and HIFs in the given microgrid.

Fault currents mostly have high magnitudes and may be damaging for the equipment. [16] proposes a method for Fault Current Management (FCM) by employing the power electronics interfaces for fault control in Inverter based Distributed Generator (IBDGs) system. Implementation in a standard IEEE 33-bus distribution system validates effectiveness of this method. By utilizing the time linear state space model in MATPOWER [17] suggesting necessity of a Fault Detection, Identification and Isolation (FDII) model. This method is also able to detect malicious attacks by intruders to avoid wrong discrepancy in demand of electric power. Cyber-attacks are very harmful for a smart grid. [17] presents a mathematical model of the system to analyze the weaknesses and suggests a robust security model for the smart grid using Kalman filter to measure the system variable and protect against false signals. A combination of intelligent computational techniques i.e., Adaptive Neuro Fuzzy Inference System (ANFIS), multiresolution analysis and ANN directs the grids towards adoption of these smart strategies, as presented by [18] for the smart localization of faults. By analyzing typical challenges, e.g., fault impedance, fault distance, power angle and angle of fault inception, this algorithm deliberately shows its resilience and trustworthiness under different fault situations. The adaptation of a combination of adaptive neuro-fuzzy inference systems (ANFIS) enhances performance over traditional methods.

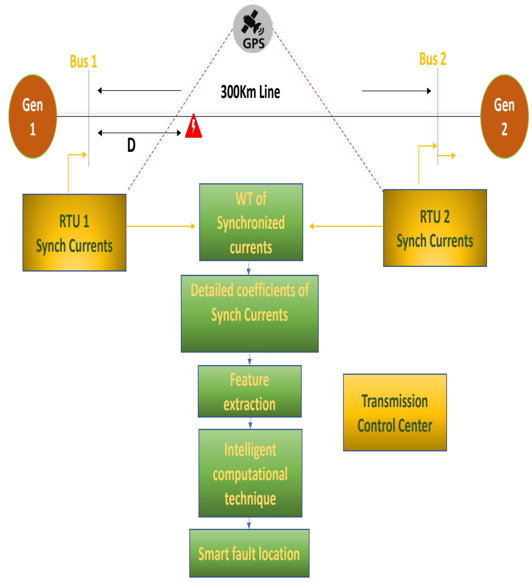


Fig. 9 model under consideration [18]

[19] presents a fault prediction, identification, and localization method based Matching Pursuit Decomposition (MPD) using Gaussian atom dictionary, voltage variation characteristics and Hidden Markov Model (HMM) of real-time frequency and fault contour plots produced by machine learning procedures in Smart Grid (SG) systems. A clustering procedure is then produced and utilized to create clusters of the voltage and frequency signal data into different symbols. Utilizing these symbols, two HMMs for detection are trained for effective fault identification to differentiate between abnormal and normal Smart Grid states. More identification HMMs are also trained over various system faulty conditions, and upon occurrence of a fault, the same trained HMMs act to classify different types of faults.

A method [20] namely One Class Classifier is a kind of clustering approach. It is for modelling and identifying faults in a practical smart grid, which supplies electricity to the entire town of Rome, Italy. This method works on the basis of a combined approach of one-class classification and dissimilarity measures learning techniques powered by genetic algorithm for optimization. This technique is able to provide soft and hard decisions regarding the identification of a test pattern.

Focusing on single-phase grounding (SPG) faults, [21] gives fault positioning technique in neutral point ineffectively grounded node of distribution network by using Support Vector Machine techniques (SVM) and Discrete Wavelet Transform (DWT).

A new bi-terminal traveling-wave-based fault localization algorithm forwarded by [24], which does not need synchronized data. The fault locator procedures have been applied using the real-time digital simulator (RTDS).

[25] emphases on the observing and classifying the faults on electric transmission line using ANNs. Feed Forward NN supported by back propagation optimization procedure has been used for fault observation and classification for analysis of each of the three phases. By examining the simulation results, it may be concluded that this method relying upon Neural Network is effective in fault recognition and classification particularly on transmission line with suitable performances. The correlation plot and confusion matrix for both outcomes depict excellent performance of this method.

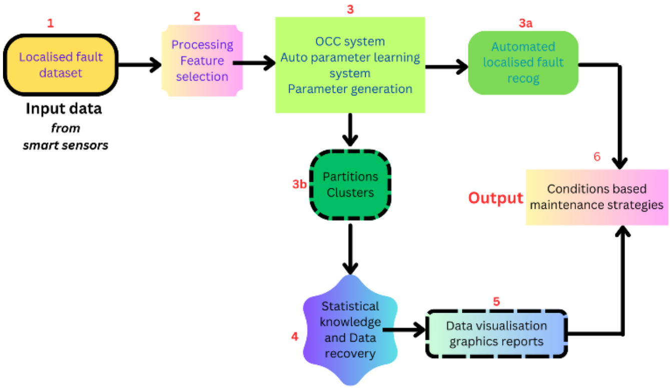


Fig. 10 **Flow diagram process describing the "ACEA Smart Grid Project" [20]**

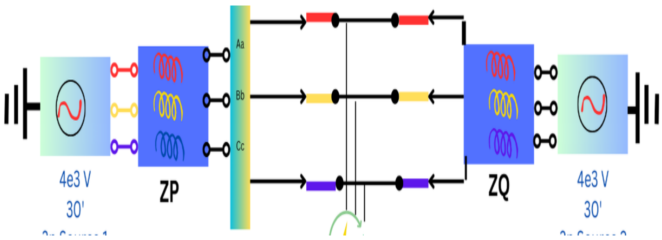


Fig. 11 **Model under study [25]**

Optimal synchro-phasor measurement devices selection algorithm (OSMDSA) [26] algorithm is a method of large data extraction for SGs and its implementation in analysis of causal impact, fault detection and identification, and which intends to deliver substantial reduction in data size while preserving detailed information from synchro-phasor measurement in temporal and spatial spheres. To validate the efficiency of this method, SG situational response is examined based on HMMs-based fault identification and classification using the space-time features generated from the minimized set of data. The said scheme when applied on IEEE39-bus and 118-bus systems confirms the robustness and minimal performance trade-offs of this approach. The numerical results and their comparisons with other similar methods demonstrate the effectualness and stiffness of the proposed analytical approach in synchro-phasor based big set of data. Dehghani, M et.al proposed in [27], the amalgamation of fuzzy logic and wavelet singular entropy to be utilized in finding faults in transmission lines in the existence of distributed generating sources in system.

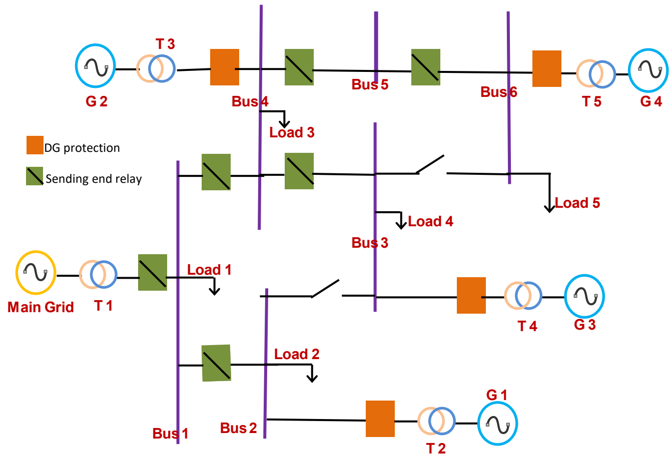


Fig. 12 **The IEC standard MG system [28]**

4. INTELLIGENT FAULT DETECTION, IDENTIFICATION AND ISOLATION (FDII)

This section discusses the machine learning based methods and algorithms in Smart Grids for fault identification, type of fault and its localization and methods to separate the faulty portion of the system from the remainder of the system.

3.1 Literature review on intelligent FDII

The following table summarizes the various FDII techniques applied in smart grid.

Table 3 **Intelligent Fault Detection, Identification and Isolation**

S.No	Author	Year	Objective	Technique	Strength	Shortcomings
1	Lin et.al [60]	2011	FD	Traditional (Travelling waves Impedance	simplicity and ease of operation	classification ability and high detection time
2	Tanwani et.al [6]	2011	FDI	time linear state space model	closer to observer based	old technique
3	Shahid et.al [11]	2012	FDC	Attribute Quarter-Sphere Support Vector Machine (AQSSVM)	Inexpensive and can-do multi-class classification	Focused on Transmission Lines
4	Sharma, N.K et.al [61]	2019	FD	PMU based	more accurate	costly and increased chances of cyber attack
5	Milioudis et.al [12]	2012	HIF FD	Signal processing (superposition on power line)	Practically application in Greek MV distribution network	Prone to interference and cyber attacks
6	Lopes et.al [24]	2014		Travelling waves Impedance	simplicity and Ease of operation	classification ability and more detection time
7	Jamil et.al [25]	2015	FDC	ANN	Simple and easy	Less efficient
8	Jiang et.al [26]	2016	FDC	Spatial-Temporal Synchro-phasor Data Characterization	Effective, accurate and stiff	Complex

9	Dehghani et.al [27]	2016	FDC	Signal Processing (Wavelet Transform)	Good fault diagnosis	Setting thresholds is difficult
10	Samantaray et.al [10]	2012	FD	Stockwell Transform	“	“
11	Cardoso et. al [62]	2004	FD	Machine Learning (Artificial Neural Network	Less heuristic	Needs additional software components
12	Das et.al [63]	2005	FDI	Knowledge Base (Fuzzy logic)	High accuracy	Dependent on the knowledge of the professional
13	Zhang et.al [30]	2017	FDI	Long Short-Term Memory Network	Highly accurate and less detection time	High chances of cyber attacks
14	Cairoli et.al [31]	2017	FDI.I	Signal Processing (PE)	Effective and can isolate faulty section	Slow
15	Kavi et.al [35]	2018	FDC	mathematical morphology	effective in noisy environment	need additional hardware
16	Chakraborty et.al [36]	2018	HIF detection	Signal Processing	Effective in HIF diagnosis	Need Smart meters
17	Sharma et.al [37]	2019	FDC	SVM, PMU	High Accuracy	Expert dependent
18	Zarei et.al [43]	2019	FD & Protection	negative-sequence resistance-based	Best for islanded operation, Independent of fault current magnitude	Setting thresholds is difficult

A feasible method for quick fault detection in Fuzzy Inference System (FIS) based LVDC microgrids is presented in [29]. A Low Voltage DC mesh bus MG is suggested that uses a two-way solid-state switch with slave and master controllers. This protection method includes efficient controllers which have the ability to detect faults quickly than the existing approaches. Moreover, the faulty section is isolated to avoid overall system shutdown. Proposing a data-driven approach using Long Short-Term Memory (LSTM) supported by Support Vector Machine network in [30], fault detection in power transmission and distribution systems. The experiments were practiced with real world data gathered from the Wangjiang grid station in China Southern Power grid, come up with accurate results.

Fault detection and localization can be more challenging, especially in the case of DC microgrids. Cairoli p et.al [31] presenting a method detecting and isolation of faulty segments in Medium Voltage Direct Current (MVDC) microgrids that create synchronization between set points of power inverters, main busbar connecting contactors and various load sections contactors for protection of MVDC systems in case of line faults. The study explains not only trip log trends based on estimation of the corresponding resistance at end of every device or entity but also provides a faults prediction algorithm which gives each entity a decision ability that does not depend on communication among the elements. Results of the experiments express that the fault current are limited, and faulty sections can be isolated in 10-20ms, and the system can be reinstated in 40-60ms.

Hilbert-Huang Transform (HHT) and ML techniques based novel microgrid protection scheme presented by [32] is a hybrid model of signal processing and machine leaning techniques. It is checked for different protection situations, e.g., the type of fault (high impedance, symmetrical an asymmetrical faults), MG structure (mesh and radial) and mode of operation (islanded and grid connected) and many more. Three different ML models are checked and compared in this setup; SVM, NBC and extreme machine learning. The comparative results depict that this technique is outstanding as compared to other SVM and NBC based classification algorithms in the context of fault event in different network topologies.

The use of combination of Smart Meters (SMs), Phasor Measurement Units (PMU)and Power Quality Analyzers (PQA), it is easy to extract and analyze efficiently, the massive amount of data furnished by these devices. According to [33], author argues that modern ML methods such as GRIP, Early-Warn are helpful and may use the collected data to warn early or to predict the faults and instabilities occurring in the grid both on a major system level for example, frequency oscillations amongst generators, and on the minor local level for example in case of line failure. The above stated technique was applied on Norwegian 22-400 Kv and 33-400kv grid system. Ridgelet Probabilistic Neural Network (RPNN) as discussed by Ahmadipour et.al [34], a useful ML technique that is able to predict islanding and none islanding states of the system under study.

Another method for prediction and classification of power networkfaults including high-impedance faults (HIFs) utilizes mathematical morphology (MM) fault detecting technique is discussed by [35].

Smart meters (SMs) as discussed before have application in the High Impedance Faults (HIFs) detection in distribution systems. It is of great importance because HIFs that occur don’t produce adequate fault current mostly not detectable by traditional overcurrent fuses, relays or others sensors. Hence the detection of HIFs on distribution systems becomes a significant challenge to protection engineers. Lack of availability of measuring equipment near the faulty positions makes HIF detection more problematic. The voltage measurements of SMs to address this issue have been discussed by Chakraborty et.al in [36]. The method discussed has the capability to detect HIFs dependent on the number of available, even harmonics in the waveform of system voltage. The performance of the scheme has been evaluated using both experimental set-up and PSCAD simulations. It has also been available for implementation on a commercial electric energy meter to show its practicability. The above stated method implanted in two main steps: initially detecting HIF by a SM using Even Harmonic Distortion Index (EHDI) calculated over system’s voltage wave form. 2. Secondly informing the distribution substation about the detection of HIF using inherent communication ability of SM.

A phasor measurement unit (PMU) allows the aquisition of phasor data at a fast-sampling rate of almost tens of samples per second. A PMU based broad area phase angle criteria is presented in [37] for making a protective scheme for the microgrid wherein the rate of change of phase angle of voltage ΦVph, is used for detecting faulty states.

In [38], there is another PMU based method supported by a multiclass SVM classifier that is capable to accurately categorize the various events. The main subject of the study in [39] is the detection of network irregularities /anomalies that extend from tiny changes in impedance at network terminals to a less or more noticeable electrical fault. This paper suggests the usage of Power Line Communication modems as sensors for prediction, classification and localization of various anomalies of the given SG. A novel method for Distributed Power Generation islanding utilising Multi-gene Genetic Programming (MGP is forwarded by in [40] by Pedrino et.al.

SVM in this regard is also utilized by [41]. This article proves the effectiveness of the SVM-based algorithm for grid's islanding and other faults detection in low-voltage level distribution grids, specifically in real-life PV power plants. As given in following fig, the data of seven key features active and reactive Power, Frequency, RMS current and voltage, Total Harmonic Distortion in current (THDi) and Total Harmonic Distortion in voltage (THDv) makes the algorithm robust to accurately distinguish between islanding and other sort of grid fault events. The proposed method is recommended due to its passive nature, ensuring minimal impact on power quality and reliable performance due to high sampling frequency.

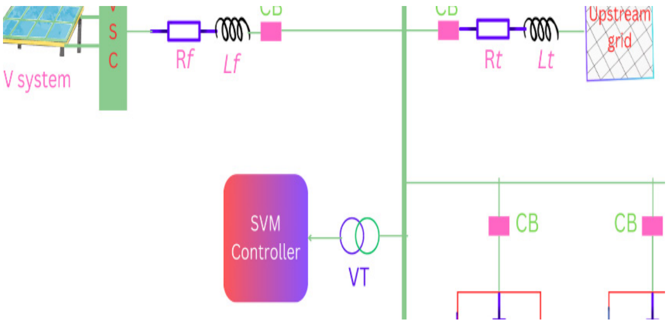
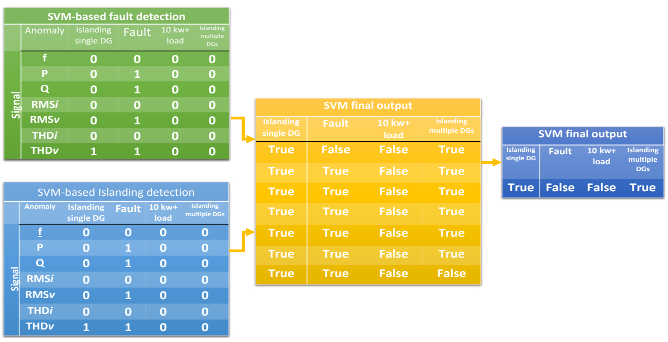


Fig. 13 Single Line Diagram of microgrid based on a practical study [41]



SVM-based fault detection

Signal	Anomaly	Islanding single DG	Fault	10 kw+ load	Islanding multiple DGs
	f	0	0	0	0
	P	0	1	0	0
	Q	0	1	0	0
	RMS*i*	0	0	0	0
	RMS*v*	0	1	0	0
	THD*i*	0	0	0	0
	THD*v*	1	1	0	0

SVM-based Islanding detection

Signal	Anomaly	Islanding single DG	Fault	10 kw+ load	Islanding multiple DGs
	f	0	0	0	0
	P	0	1	0	0
	Q	0	1	0	0
	RMS*i*	0	0	0	0
	RMS*v*	0	1	0	0
	THD*i*	0	0	0	0
	THD*v*	1	1	0	0

SVM final output

Islanding single DG	Fault	10 kw+ load	Islanding multiple DGs
True	False	False	True
True	True	False	True
True	True	False	True
True	True	False	True
True	True	False	True
True	True	False	True
True	True	False	False

SVM final output

Islanding single DG	Fault	10 kw+ load	Islanding multiple DGs
True	False	False	True

Fig. 14 Algorithm based on connected and islanded fault detection SVM module [41]

An enhanced K-NN technique in this regard is also helpful, presented by Hosseinzadeh et.al in [42]. They came up with a combination of ML methods that are combined for fault detection. The main theme of this technique lies on the Linear Discriminant Analysis and Principal Component Analysis. The earlier is used to reduce the dimension of the data matrices. The applied PCA not only decreases the size of the dataset but also abolishes the probability of uniqueness of given data. The LDA scheme is then applied to the output dataset of the PCA to further decrease within class distance of the dataset and simultaneously increase the distance between different classes. Lastly, the renowned K-NN scheme is utilized to finalize a set of data to detect any kind of the fault and determine its class The KNN scheme supported with LDA and PCA is hereby used to predict and identify various faults within a smart grid. The said scheme works in the following 3 steps; 1. By using PCA, which simply uses matrix operation and statistical analyses to compute a projection of the actual data into smaller number of dimensions used on the whole input dataset. 2.Then, the LDA is used for finding a similar combination of characteristics to minimize the events. 3. Lastly, the KNN investigates received data to properly categorize the input data into its relevant class. The flowchart of these steps is as given below. From results, one may find the effectiveness and robustness of this scheme in classification of various types of faults arising in the smart grids.

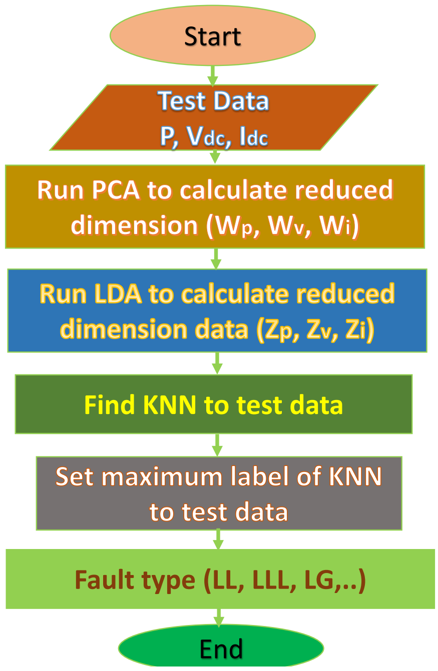


Fig. 15 Flowchart of classification technique [42]

A new voltage frequency control method, best for islanded operation as given in [43], presents a novel fault detection and protection strategy tailored for islanded inverter-based (IB) microgrids (IBMGs) with voltage-frequency controlled IB distributed energy resources (VF-IBDERs). Addressing the challenges posed by bi-directional and limited fault currents in IBMGs, this approach introduces a voltage-dependent negative sequence resistance-based method for fault identification. Unlike conventional methods, this technique is independent of magnitude of fault current, enabling reliable detection and direction identification without requiring a communication infrastructure. Simulation results under various fault scenarios in the Power System CAD/EMTDC environment confirm the effectiveness of this strategy, demonstrating its reliability and adaptability in ensuring fault detection and classification for islanded IBMGs.

The method proposed by [44] is based basically on Discrete Wavelet Transform for feature data abstraction and associated with Restricted Boltzmann Machine (RBM) with artificial neural network to deliver accurate classification. model achieved near 100% fault detection accuracy across all fault types. comparison with kernel extreme learning machines (KELM), Support Vector Machine (SVM) and multi-KELM confirming its stability and reliability in challenging environments.

Phaslets can successfully calculate the phasors from given data layers, ubound to a numeric multiple of a half cycle. A Signal Processing (SP) method based on said phaselets method has been discussed in [45] to predict islanding state. This method has the ability to sense isolation in less than couple of frequency cycles without power quality degradation and Zero Non-Detection Zone (NDZ). Advanced online monitoring structure supported by machine learning methods for rapid and accurate fault detection. The system discussed in [46] integrates a pseudo-continuous quadrature wavelet transform (PCQ-WT) feature extraction mechanism by means of a improved Gabor wavelet with a solid CNN-based incident detection technique in electric systems.

The proposed approach in [47] is an innovative and robust Microgrid Protection Scheme (MPS) for fault detection and identification, a vital component for enabling smart grids, combines Maximal Overlap Discrete Wavelet Transform (MODWT) using the FejerKorovkin wavelet and an Extreme Gradient Boost (XGBoost) classifier, making it a novel solution for microgrid fault protection. Another signal processing multi-variable passive islanding detection method (IDM) as presented by Swarnkar et.al in [48] by using the parameters obtained by voltage signals processing. Negative Sequence Voltage and Negative Sequence Current Transform by Hilbert Transform and Stockwell transform to calculate Multiitem Islanding Detection Factor (MIDF). This method is better than DWT, EMD and Slanlet Transform etc. In [49], a hybrid, unsupervised clustering-based approach for detecting bad PMU data in real-time with minimal computational overhead. Three clustering techniques- density-based spatial clustering of application with noise (DBSCAN), linear regression and Gaussian mixture models (GMM) are grouped to improve detection accuracy. The study [50] proposes an anomaly-based fault identification approach that identifies deviations from normal system behavior, utilizing two models: PCA and single-class SVM. Here single-class SVM predicts more fault data points than the PCA model, while the PCA detects more normal points as compared to SVM model. VSB power line fault recognition dataset in Azure Machine Learning (AZML) workspace is utilized as an environment to carry out experimentations.

Smart grids are exposed to cybersecurity threats and attacks. [51] proposes a micro synchro-phasor or μPMU-based fault detection algorithm. Simulation in Simulink (MATLAB) results showing fewer probabilities of cyber-attack. Hybrid smart grid fault detection system based on cloud-edge is proposed in [52]. Cloud-edge detection may need uploading a huge volume of data resultantly undergoing long network delay. A combination of three computational tools as stated in [53] et.al gives: Signal Processing (SP) utilizing the well-known Maximal Overlap Discrete Wavelet Transform (MODWT), machine learning using SVM and optimization procedure by the Augmented Langrangian PSO (ALPSO). A detailed assessment study of Association for Electric Reliabilty Technology Solutions on microgrids and IEEE 34-bus system approves that the scheme is fast, accurate, and robust to noisy conditions however it is a complicated system. Feature extraction MATLAB, Train/test in Python [54] communication-free islanding recognition Recurrent Neural Network based method for distributed generation that comprises of both inverter-based DG and synchronous devices. This strategy contains three stages: temporal data extraction from the voltage signals at the point of joint coupling, parameter extraction utilizing the wrapper technique and eventually using LSTM reinforced RNN method. The author, in [55] proposes an enhanced HIF identification and detection method that is based on a Kernel Extreme Machine Learning (KELM). This method works in two steps; First feature extraction based on DWT and Hilbert-Huang Transform (HHT), then HIF identification method by the advance learning algorithm i.e., Kernel Extreme Machine Learning (KELM).

Another ELM algorithm presented in [56] is a self-activating and simple classifier for detection of network faults. ELM model relative to a traditional ANN model proved comparatively a less time consuming and minimum computational complication. Utilizing MATLAB for classification and Python for optimization, [57] presents SVM to predict power system instability before occurring an unstable condition. It is helpful in smart grids fault identification and classification. Wildbeest Herd Optimization is a new metaheuristic global optimization algorithm [58] gives a WHO-optimized random forest and decision tree algorithm supported by ANFIS fault identification scheme. CNN, LSTM, and Hybrid CNN-LSTM approach for FCD is discussed in [59]. CNN excerpts feature from the collected signals, LSTM utilizes these characteristics to make correct estimates to detect faults.

Load forecasting is another key aspect of a Smart Grid as discussed in [66] using genetic harmony search algorithm for optimization of parameters. Forecasting helps to keep a nice balance between load and source to avoid grid failure. In [67], the authors proposed a three modular technique for load forecasting. Management of load end is important in load forecasting of a smart grid. Efficient demand side management optimization algorithms are proposed by authors in [68,69]. Smart grids, being computer oriented remote-controlled structures for overseeing and supervising electricity distribution, are susceptible to cyber-attacks. Some of the common cyber security risks posed to a smart grid. False data injection (FDI): False data injection involves introducing erroneous data into system, often targeting measurement reading e.g., voltage, power and frequency. This can compromise the integrity and reliability of the system. For mitigation of such attacks, data validation, access control and anomaly detection techniques [70-72] are used. The other common risk is Man in the Middle (MitM), it is a sort of privacy breach attack that can leak device protocol and other sensitive data. Physical Unclonable Function (PUF) authentication mechanism [73,74] can be used to detect such attacks. Adversarial attacks are another common risk for smart grid networks to disrupt operations or interfere normal operation of the system. For the mitigation of such threats a robust architecture and well adversarial detection technique is helpful.

5. CONCLUSION

Smart grids save operating time, preventing equipment damage and harm to living things. They have the capability of accommodating the renewable resources of energy and encourage distributed generation to minimize carbon emission. Although smart grids have become an unavoidable contemporary need and there is no way of denying this powerful and state of the art technology. However, they have some limitations and difficulties as described in the table. Cyber criminals intentionally attack these systems to interrupt operations or take unauthorized control of the system, resulting risks such as substantial outages and economic losses. Cyber assault if successful, may compromise important information and even take complete control of the power network, subsequently maneuvering system operations, The severeness of attacks depends on their effectiveness and complexity of security standards. ML based are developing day by day and an improved version of every ML/AI is available, so the implementation of the latest technique is quite helpful for improvement of fault detection, identification and isolation. As discussed above, PMUs are also a sensitive measurement tool, so the deployment of PMUs may be promising for improved FDII. Effective ML/AI methods for this purpose may become more effective, if utilized as a combination. Cyber security issues should be addressed properly. We hope that this response comes up to your expectations.

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